To overcome some of these defects in the present inquiry the precipitation records have been weighted to accentuate the favorable and to diminish the unfavorable aspects of location; and the investigated group has been enlarged to include several stations not on the watersheds, to correct the defect of dearth of records as far as possible. Furthermore, of the available precipitation records, only selected months were used, rather than the calendar or any other year, having in mind always that the group or unit should serve only as an indicator.

The results shown herein are from precipitation for October to April just preceding the May to August discharge period. The precipatation stations finally used (with their altitudes and average annual precipitation in inches for general information). are as follows: Silver Lake in Brighton Basin, 8,700 feet above sea level, 43 inches annual precipitation; Cottonwood Weir in the mouth of Big Cottonwood Canyon, 4,992 and 22; Lower Mill Creek, about 4 miles south of Cottonwood Weir, 4,959 and 23; Salt Lake City, 4,408 and 16; Midvale 12 miles south of Salt Lake City, 4,365 and 16; Snake Creek, 6 miles southeast of Silver Lake and beyond a high divide, 5,950 and 24; and Heber about 12 miles southeast of Silver Lake, 5,593 and 17. Only Silver Lake and Cottonwood Weir are on the watershed.

Employing precipitation group No. 2 (Silver Lake, 3 times Snake Creek, and 4 times Heber) as a unit for the 10 years of concurrent record, and reducing it to percentages for comparing with the percentages of discharge for the same period, the average deviation was found to be only 6.5 per cent. Precisely the same average deviation was shown by the use of precipitation group No. 5 (Salt Lake City, Silver Lake, 2 times Cottonwood Weir, 5 times Snake Creek, and 6 times Heber) for 8 years of concurrent record.

But testing the relationship by the use of a more trustworthy method, from the original precipitation and stream discharge data, the correlation coefficient for group No. 2, 10 years, was found to be 0.914 plus or minus 0.035; and for group No. 5, 0.979 plus or minus 0.010. The latter is a rather remarkable correlation, due in part probably to chance in so short a record. The original snow survey data for this same 8-year period shows a correlation coefficient of 0.683 plus or minus 0.127, not very satisfactory, though it probably would be improved by a longer record.

Precipitation records as indicators of stream discharge are also very valuable because they apply to other nearby watersheds to a certain extent. For instance, precipitation group No. 2, 10 years, paralleled with the combined original data for the discharge of the two Cottonwood streams, gives a correlation coefficient of 0.921 plus or minus 0.032; while the Brighton Basin snow survey original data gave a correlation coefficient of only 0.608 plus or minus 0.134, when paired with Big and Little Cottonwood Creeks combined.

Similarly, precipitation group No. 5, 8 years, shows a correlation coefficient with the two Cottonwoods combined of plus 0.950 ($\pm$0.023); while the snow-survey correlation coefficient for the same period is only 0.493 plus or minus 0.180. This has practically no predictive value, though it may be due in part to the shortness of record available.

It will not be forgotten that snow measurement sites or stations, like precipitation stations, should be regarded as indicators only; though where their locations are suitable, very good results may be obtained. Furthermore, where there is a scarcity of precipitation records or the tenure of precipitation stations is insecure, the snow survey is, in most watersheds, a convenient and satisfactory substitute.

WHIRLWINDS AT OIL-TANK FIRE, SAN LUIS OBISPO, CALIF.

551.515:(794)
614.481

By J. E. Hissong

[U. S. Weather Bureau Office, San Luis Obispo, Calif., April 17, 1926

On the morning of April 7, 1926, following a showery night, several mild lightning discharges were noticed in the south, the first at 7:15 a. m., followed by rumbling of thunder in the distance. At 7:35 a. m. a very intense discharge of lightning occurred accompanied by a crash of thunder; this was followed instantly by a terrific explosion that shook the town of San Luis Obispo severely. About 20 large plate-glass windows in store fronts were completely shattered, numerous small windows in residences were broken, houses rocked on their foundations and hundreds of people rushed into the streets, many under the impression that a severe earthquake shock had occurred. The lightning bolt had struck the large oil reservoirs at the tank farm of the Union Oil Co., located about 2½ miles directly south of the center of the town, and the oil, or the vapor in or over three of the reservoirs had exploded, setting them on fire. These reservoirs have a capacity of 750,000 barrels and were full.

An employee of the oil company, who was looking toward the reservoirs at the time of the explosion, said: "I saw two balls of lightning strike reservoirs No. 5 and No. 7; a clap of thunder and an explosion followed immediately and the tanks burst into flames. At the same time the earth rocked so violently under my feet that I was almost thrown down."

A fourth reservoir was fired and exploded about 15 minutes later. Testimony as to the cause of the explosion of this reservoir is conflicting. An inspector for the oil company reported that it was struck by another lightning discharge. Others in the vicinity say that the first explosion threw burning timbers from the roofs of the exploded reservoirs, and possibly burning oil, on the fourth reservoir, causing it to explode.

Approximately 6,000,000 barrels of oil was stored at the farm in concrete reservoirs and steel tanks. With the exception of five of the smaller steel tanks, containing about 250,000 barrels of oil, all the oil burned during the five days of the fire.

Typical thunderstorm conditions prevailed at San Luis Obispo during the morning of the 7th. A storm which had been developing over the ocean between the California coast and the Hawaiian Islands for several days had increased in intensity and moved northeastward during the night. Its center on the morning of the 7th was approximately 600 miles west of San Francisco, the lowest barometer reading near the center being close to 29.00 inches. The thunderstorm was, therefore, about 700 miles southeast of the center of the low-pressure area. A moderate southeast wind had prevailed during the night and had increased to 18 miles per hour after 5:00 a. m. About 7:20 a. m. the wind changed to southwest, blowing out of the approaching squall, and increased to 24 miles per hour. At the same time a heavy downpour began, 0.18 inch of rain falling in three min-

(To face p. 161)

utes. The temperature dropped 12° and the barometer rose from 29.45 inches to 29.55 inches within a few minutes. Near the peak of the rise on the barogram appears a vertical mark, approximately 1/8 inch in length, caused by the concussion due to the explosion. This mark covers any record of an air billow or wave that may have traveled over the station. Such an air wave would traverse the distance to the station in about 12 seconds—too short a period to make a record on the barogram distinct from that made by the concussion.

The thunderstorm continued with moderate rainfall and occasional feeble lightning until 10:42 a. m. when the rain ended. The last lightning was observed at 8:30 a. m.

This storm was not severe and with the exception of the single heavy lightning discharge would not have called for comment, but the fire that was caused by the lightning burned five days and resulted in the loss of two lives and of property estimated by responsible officials of the oil company at $15,000,000. It also produced hundreds of violent whirlwinds, many of tornadic character and force, probably the strangest meteorological phenomenon ever noted in connection with a fire. In fact one of these whirls was responsible for the loss of life noted above.

Strong southerly winds prevailed all day on the 7th and until 12:20 a. m. on the 8th, shortly after midnight, when the wind veered into the west and a few minutes later into the northwest.

At the same time the first "boil-over" occurred; reservoirs Nos. 5, 6, and 7, and, according to some reports, No. 3 also, boiling over at the same time. These are all 750,000 barrel containers. They threw out an immense quantity of hot, burning oil which spread with remarkable rapidity over an area estimated by the engineers present at about 900 acres. The flames leaped seemingly a thousand feet in the air over the greatly increased area of the fire. At the same time violent whirlwinds began to form over the fire.

One of these whirlwinds left the vicinity of the reservoirs and traveling east-northeast about 1,000 yards picked up the Seeber cottage, just outside of the tank farm, lifting it several feet in the air and carrying it about 150 feet north, where it was dropped in a field, a total wreck. Mr. A. H. Seeber and his son, who were in the house, were killed. A daughter and a friend, who had just stepped out of the house, were carried some distance along the ground, but were not seriously injured. A barn, 100 feet south of the house, was not damaged. A few minutes later, a whirl, possibly the same one, tore the roof from the house of Mr. Banks, about one-fourth mile northeast of the Seeber home; it also demolished his garage and other outhouses, uprooted fruit trees, and drove a 2 by 4 inch beam, 16 feet long, through the boarded side of the pump house. An examination of the débris scattered around the Seeber and Banks places indicates clearly that the direction of rotation in these funnels was counterclockwise. Several of the fruit trees in the Banks yard, that were not uprooted, were twisted around in a counterclockwise direction until the boles cracked. Some of the whirlwinds, however, were reported as rotating in the opposite direction. At least two were observed, on the 8th during daylight hours, revolving in a clockwise direction. These were reported by eye witnesses who were in a position to observe them carefully.

Between 12:30 a. m. and 3:00 a. m. on the 8th, when the great sea of oil was burning and the tornadoes appear to have been most numerous, houses in San Luis Obispo, 2½ miles distant, shook as if a moderate earthquake were passing. Windows rattled vigorously and continuously and the Weather Bureau building swayed noticeably at times. The roar, even at that distance, was terrifying. Many residents refused to remain in their houses. About 3 a. m. these vibrations subsided.

From the time the wind veered into the northwest and the large reservoirs boiled over, hundreds of whirlwinds formed in and around the edges of the fire until the last tank boiled over on the morning of the 11th. During the period when the large reservoirs were burning and the temperature over the fire was probably at its highest point, and consequently the vertical convection was strongest, the whirls appear to have been most numerous and violent. Many of them had all the characteristics of true tornadoes. The gyrating, writhing, funnel-shaped clouds were viewed by thousands, the white, condensing vapor in the vortices making them plainly visible against the background of black smoke. Some of the funnels appeared to be not more than one foot in diameter at the smallest part, and some were reported as giving the impression of ropes dangling from the clouds of smoke.

About the time the Seeber house was destroyed, an employee of the oil company who had left his car standing near the Seeber barn started in that direction, but becoming alarmed at the roaring from the burning reservoirs, ran back to the Edna road and started toward town. Looking back he saw a "funnel" leave the fire and move toward the road, in a northeasterly direction. Near the mushroom-shaped top of the funnel, about 200 feet in the air, a small shed or chicken coop was floating around in a counterclockwise direction. Looking back occasionally as he fled Mr. Berry says that he saw at least 20 "spouts" between the Seeber house and the fire, some of them very small. He reports that a brisk northwest wind was blowing at that time, and that the roar from the whirlwinds was terrific.

It is believed that none of the tornadoes traveled more than 3 miles from the fire zone; some débris was found at that distance.

About 10:30 a. m. on the 8th, a tornado traveling from the reservoirs picked up Mr. Martin's house, about 300 feet north of the site of the Seeber home, and, according to spectators, raised it 300 feet in the funnel. It was carried about 100 feet northwest and dropped, completely demolished. A small range of hills about 500 feet in height lies northwest of the Martin house and may have been the cause of this tornado apparently traveling against the northwest wind. It is probable that an eddy formed in the lee of these hills.

Practically every explosion or "boil-over" of a reservoir or tank produced whirlwinds or tornadoes. Melted cast iron fittings found at the scene of the fire indicates a temperature of between 2,000° and 2,500° F.

The tank farm lies on the broad, level floor of San Luis Valley. From this valley the Los Osos Valley, a broad, level plain, trends northwestward to the ocean, about 13 miles from the tank farm. Northwest winds through this valley are of such strength that they have received the local name of "the Osos wind." On Sunday afternoon, April 11, when the writer visited the tank farm, he estimated the northwest wind then blowing across the farm at 40 to 50 miles per hour. It was with difficulty that one could walk around the rims of the large reservoirs. The wind velocity registered at the station at this time was 15 miles per hour. In view of the fact that the tornadoes were first noted just after the wind changed from southerly to northwest it is possible that they may have been caused by the strong convectional currents over the fire being given a rotational motion by the northwest wind.

Property to the value of $15,000,000 was destroyed by fire and wind.

Supplementary note.—Mr. Hissong has sent to the editor five photographs of whirls that accompanied the oil fire. Since these probably constitute a unique record of a phenomenon which is rarely developed to the degree of intensity here met with, the photographs are reproduced, without retouching, and in the same size as the originals. They are arranged in what appears to have been the order in which they were taken.

Following, is an extract from Mr. Hissong's letter which accompanied the photographs:

It will be noted that the funnels were photographed after leaving the smoke pall that lay over the fire, the faint outlines of distant hills being visible in the background. Also that the funnels appear black in the prints although all accounts of eyewitnesses were to to the effect that they were white, or light colored. This is probably due to the fact that the funnels were between the camera and the sun * * *. The camera was pointing due south. The pictures were taken just after noon on the 8th.

Regarding the distance traveled by the whirls: Some dèbris was found on the slopes of the Santa Lucia range about 3 miles northeast of the fire. This range rises rather abruptly to a height of about 2,500 feet above the floor of the valley and undoubtedly some of the whirls were broken up by this range during the night of the 7–8th. No whirls were seen more than a mile from the fire during daylight hours.

Since writing the report I have learned that a house about 4½ miles south of the tank farm was unroofed about 7 a. m. on the 7th by a violent wind. This was probably the same storm that caused the fire. No lightning was noted in that vicinity, however, and no funnel-shaped cloud was seen.

551.515 (492)

AEROLOGICAL EVIDENCE AS TO THE CAUSES OF TORNADOES

[Based on Dr. E. van Everdingen's "The Cyclone-like Whirlwinds of August 10, 1925," which was published in English in Proc. Koninklijke Akademie van Wetenschappen te Amsterdam, vol. 28, No. 10. Abstract and note by B. M. Varney]

It is remarkable that in the United States, more afflicted with tornadoes than any other area of equal size on the globe, the literature of tornadoes since Ferrel is confined almost exclusively to compilations of statistics on distribution, frequencies of occurrence, descriptions of resulting damage, and so on. We are therefore fortunate in being able to present excerpts from an aerological study by Doctor van Everdingen, of an extensive series of whirlwinds which caused widespread destruction in southern, central, and eastern Holland on August 10, 1925.

The paper opens with a brief statistical survey of whirlwinds of destructive violence in Holland. A total of 82 such has been recorded during the period 1882–1925. The monthly frequency was as follows:

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1	2	2	3	9	11	20	19	9	2	4	-----

For the great destruction of August 10, 1925, extensive evidence as to the direction of fall of trees and parts of buildings, distribution and shape of damaged areas, etc., leads to the conclusion that many whirls, decending to the earth's surface intermittently, were involved. None of them appears to have caused wreckage over paths of the lengths frequently found in the United States. The whirlwinds occurred in connection with the passage across the region of a trough of low pressure, accompanied by a thunderstorm of no unusual intensity.

Relative to the pressure distributions at the surface over Holland during the afternoon, there is presented a series of charts for 2, 4, 5, 6, 6:30 and 7 p. m. Commenting on these, Doctor van Everdingen says:

Only at the moment of the passing of the whirlwinds extraordinary isobars are displayed, but these are very remarkable indeed, as in the neighborhood of the tracks of the whirlwinds, they indicate pressure gradients up to 55 mm. per degree, which, if occurring over larger areas and longer periods, would cause hurricanes of the most destructive kind.

With isobars of curvature as here occurs, however, by far the greater part of the gradient is required for change of direction, and moreover it is evident that this pressure distribution did not persist long enough to develop its full wind force. There are no indications of the occurrence of similar gradients farther southwest before the whirlwinds appeared. Therefore though we don't exclude the possibility, that in the first place northwesterly gales and whirlwinds with a southerly track may be explained by these pressure gradients, we are of opinion, that on the whole these phenomena are to be regarded rather as sequences of than as causes for the formation of the whirlwinds. * * *

We turn to the aerological side of the study:

In consequence of the constantly increasing application of the investigation of the upper air to the daily forecasts of the weather, we have at our disposal rather complete material of temperatures and velocities of the air in the lower kilometers. By means of aeroplanes the temperature was determined up to a considerable height at Duxford in England, Uccle in Belgium, Helder and Soesterberg in our country, by means of kites or cable balloons at Lindenberg and Friedrichshafen in Germany. Moreover, observations from mountain stations were available in Germany, Switzerland, and France. Numerous observations of pilot balloons give the wind directions in the higher strata at various times of the day.

The morning observations showed large differences of temperature between England and Central Europe at the 1,000 and 2,000 m. levels. Above the Puy de Dome in south central France the temperature was 68° F. at 1,500 m., and it is assumed that this temperature was characteristic of central France and that the southerly and southwesterly winds at that level later brought the warm air over Holland. The morning observation at Friedrichshafen on the Lake of Constance showed a steep lapse rate of temperature above 2,000 m. The assumption is made that this condition overspread Holland in the afternoon *above the warm air from the southwest*, accompanied by a temperature inversion at about 2,000 m., thus bringing about a condition which awaited only the lifting of the warm, moist air by underrunning of the much colder air from the west, to produce thunderstorms.

As first demonstrated by Margules, the gravitational force accomplishes a considerable amount of work when cold masses of air, which first were found beside the warmer masses, spread out under these. With a vertical extension of the layers of 3,000 m. and a difference of temperature of 5° C. the whole mass of air may obtain a velocity of 12 m. p. s. The sudden outbreak of stormy winds during a thunderstorm may completely be explained in this way; but velocities of 50 m. p. s. are not easily reached in this manner; for these we want the cooperation of a heavy thunderstorm squall with a whirlwind.

We now come to the observations which in our view contain the key for the explanation of the whirlwinds. The older theories, which for instance connected the whirlwinds with a rapidly rising current of air, which was said to cause vortices, or which ascribed them to the encounter of two strong wind currents of different directions in the same level, have been found to be failing in most cases. Rapidly rising currents often show no rotation at all. Air currents of very different direction and velocity occur in the same level generally only at distances, very large as compared with the diameter of a whirlwind. On the other hand it is shown daily that very different velocities may occur one *over* the other and that in that case, especially when inversions limit the turbulence, very sharp discontinuities may be found. Gradually it has become probable, that these discontinuities of the wind are necessary for the formation of vortices, and that these vortices therefore will rotate in the first instance about a horizontal axis, the higher parts showing the largest velocity in the direction of propagation. According to hydrodynamics, if friction is not considered, a vortex-thread can end only at the boundary of the fluid. Wegener and Krebs have made the supposition, that waterspouts and whirlwinds constitute the bent-down ends of the horizontal vortices in the